In-focal-plane SQUID multiplexer

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Abstract

Superconducting quantum interference device (SQUID) multiplexers make it possible to build arrays of thousands of microcalorimeters and bolometers based on superconducting transition-edge sensors (TES) with a manageable number of readout channels. Previous to this work, TES arrays were multiplexed by extracting leads from each pixel to multiplexer filter and switching elements outside of the focal plane. As the number of pixels is increased in a close-packed array, it becomes difficult to route the leads to the multiplexer. We report on the development of an in-focal-plane SQUID multiplexer to solve this problem. In this circuit, the filter and switching elements associated with each pixel fit within the pixel area so that signals are multiplexed before being extracted from the focal plane. This in-focal-plane architecture will first be used in the SCUBA-2 instrument at the James Clerk Maxwell Telescope in 2006.

Keywords: SQUID; multiplexer; transition-edge sensor; microcalorimeter; bolometer
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1. Introduction

SQUID-based multiplexers are being developed to instrument large-format arrays of TES bolometers and microcalorimeters using both time-division [1] and frequency division [2] approaches. An 8-channel time-division SQUID multiplexed array has been used in FIBRE, a tunable Fabry-Perot spectrometer deployed at the Caltech Submillimeter Observatory [3]. Frequency-division multiplexing has been demonstrated in the laboratory [4] and is planned for several instruments. In each case, wiring is routed outside the focal plane from each pixel before multiplexing.

2. SCUBA-2

The first in-focal-plane-multiplexed TES instrument will be SCUBA-2, a second-generation, wide-field submillimeter camera under development for the James Clerk Maxwell Telescope. A successor to the successful SCUBA instrument [5], SCUBA-2 will consist of over 10,000 bolometer pixels in four 32×40 subarrays at 850 μm and four 32×40 subarrays at 450 μm. System design studies indicated

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that routing wires from each pixel to the outside of the focal plane would be prohibitively complicated. We present here the design and preliminary tests of the in-focal-plane multiplexer for SCUBA-2.

The details of the bolometer and system design for SCUBA-2 are presented elsewhere [6]. We describe here the SCUBA-2 in-focal-plane multiplexer circuit. The approach taken in the SCUBA-2 in-focal-plane multiplexer may be useful in a wide variety of future arrays.

3. Time-division SQUID multiplexers

3.1. Multiplexer electrical schematic

The basic time-division SQUID multiplexer circuit is described in greater detail elsewhere [7]. Address currents are applied sequentially to turn on one row at a time of a two-dimensional array of SQUIDs (Fig. 1). Each SQUID is shunted with an address resistor ($R_A \sim 1\ \Omega$) and a coil that inductively couples to a 'summing coil' common to all of the SQUIDs in a column. The summing coil couples to a single second-stage SQUID for each column. The second-stage SQUIDs are voltage biased, and couple to a series-array SQUID at a higher temperature, which in turn couples to room-temperature electronics. The address current turns on one row of first-stage SQUIDs at a time.

Feedback to the first-stage SQUID is applied through a feedback coil common to one column of SQUIDs. When one row is turned on, a feedback signal is applied to null the error signal measured when the row was turned on during the previous frame. Custom room-temperature digital electronics [8] are used to process signals from each column, control the timing of the row multiplexing, and apply a switched feedback signal to a common feedback line for each column.

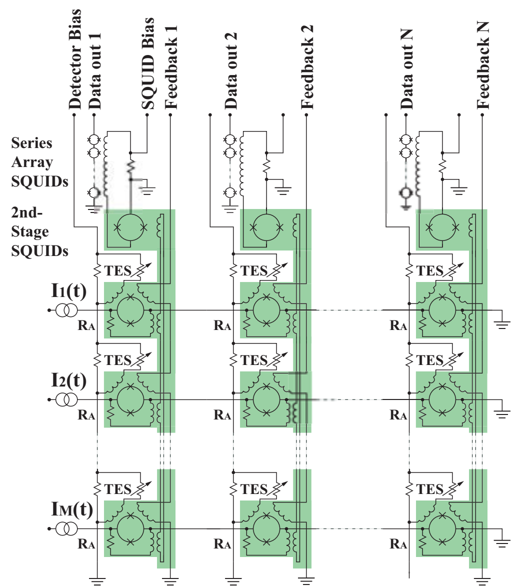

Fig. 1. The SQUID MUX circuit architecture used in the in-focal-plane multiplexer

3.2. Dark SQUID

The low-frequency noise of the amplifiers is important for some TES applications (especially bolometric applications). Square-wave chopping of the TES bias between positive and negative values can be used to remove the amplifier low-frequency noise. An alternative method for reducing low-frequency noise is to difference the output of each first-stage SQUID with the filtered output of an extra row of first-stage "dark" SQUIDs to remove correlated low-frequency noise, including the 1/f noise in the second-stage SQUID and the rest of the amplifier chain. In SCUBA-2, there are 40 rows of bolometers, but 41 rows of multiplexer channels due to the addition of a dark SQUID channel. The SCUBA-2 subarrays therefore have 32 × 40 bolometer pixels and 32 × 41 multiplexer pixels.

4. MUX pixel design

The bolometer pixels for SCUBA-2 are spaced on a 1.135 mm pitch. The SCUBA-2 multiplexer pixels fit into the same area. Each bolometer pixel is connected to multiplexer pixel through superconducting bump bonds. All SCUBA-2 multiplexer and bolometer pixels are identical, making it straightforward to use a wafer stepper for the full-wafer photolithography.

4.1. Pixel electrical schematic

The input signal is coupled into the SQUID through an input transformer to maximize the self and mutual inductance that can be fit into the pixel area. The input transformer, the column-feedback line, and the summing coil are wound as gradiometers to reduce the crosstalk. The 5 mΩ detector bias resistors are also located in the SQUID MUX pixel.

Coupling between the column feedback and the input transformers of the off pixels is a source of crosstalk. A second 'dummy' SQUID, with a feedback coil wound in the opposite direction, is used in each pixel to null this coupling. The 'dummy' SQUID is never turned on.

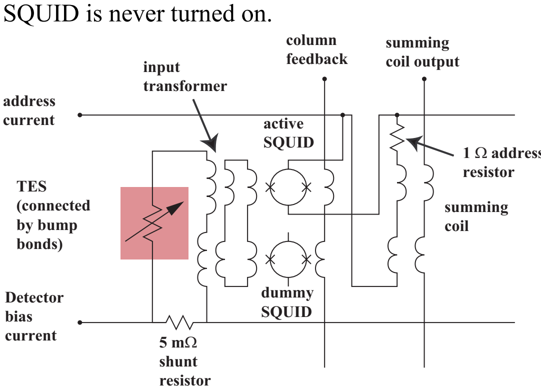

Fig. 2. The electrical schematic of the MUX pixel.

4.2. Pixel physical layout

Four different physical layouts of the SQUID MUX pixel were tested in order to select a design with the appropriate mutual inductance, self inductance, and crosstalk for SCUBA-2. In figure 3, we show the physical layout that will be used.

All leads in the MUX pixel are fabricated as striplines to reduce magnetic crosstalk, and all coils are wound as gradiometers. Flux coupling directly from the TES bolometer into the summing coil is also a possible source of crosstalk. In order to minimize this coupling, a common line of symmetry is preserved in the design of both the TES bolometer and the SQUID MUX pixel. Flux coupling directly from the TES into both sides of the summing coil gradiometer will cancel.

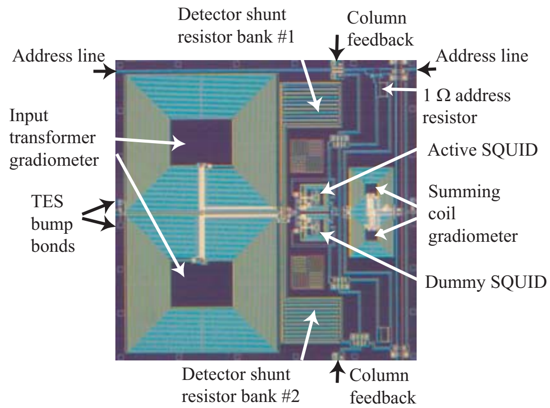

Fig. 3. Labeled photograph of a SCUBA-2 MUX pixel.

5. Test results

We have fabricated and tested four major varieties and a larger number of minor varieties of SQUID MUX pixels for SCUBA-2. A 3 × 3 array was also fabricated to test the interface between pixels in a two-dimensional array (Fig. 4).

The pixel design described here best matched the requirements of SCUBA-2. Tests were conducted at 4 K in a liquid helium dip probe. For the selected variety, the mutual inductance of the coupling to the input SQUID is 480 pH, the self inductance is 470 nH, the maximum crosstalk to distant pixels is 0.04%, and the maximum crosstalk to nearest neighbors is 0.6%. The noise at 4 K is 1.2 $\mu\Phi_0/\sqrt{Hz}$, and the predicted noise at 65 mK is 0.15 $\mu\Phi_0/\sqrt{Hz}$. We have demonstrated this noise level at 65 mK in other SQUID designs. Some other tested varieties had significantly higher inductance, and some had significantly lower crosstalk (< 0.01% for distant pixels).

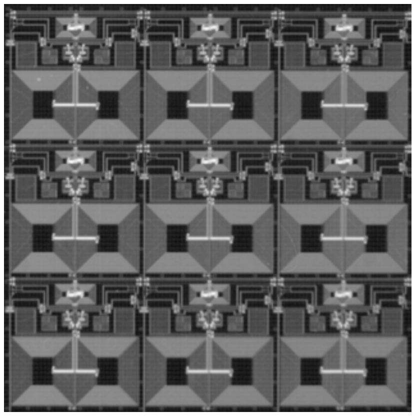

Fig. 4. Photograph of a 3 × 3 array of MUX pixels. Each pixel is 1.135 mm square.

We have calculated the degradation of the noise-equivalent power (NEP) of the SCUBA-2 bolometers due to the multiplexed amplifiers using the measured performance of the SCUBA-2 bolometer pixels. We assume that the address lines are switched at a rate of 800 kHz, and that the array is operated in the best weather, when the photon noise is lowest. In the 850 μm array, in-band and aliased amplifier noise degrade the NEP by 0.11%, and aliased bolometer noise degrades the NEP by 2.3%. In the 450 μm array, aliased amplifier noise degrade the NEP by 0.033%, and aliased bolometer noise degrades the NEP by 6.5%. These results meet instrument specifications, but it may be possible to improve the aliased bolometer noise by the implementation of noise-mitigation structures in the TES bolometers to reduce excess out-of-band noise [9,10].

6. Conclusions

The in-focal-plane MUX pixel meets the specifications for the SCUBA-2 instrument. Prototype 32 × 41 multiplexer subarrays are now in fabrication. They will be tested in a dedicated 4 K testing facility, and then bump bonded to the TES bolometer array. Testing at 65 mK will occur after hybridization.

The MUX pixels can be made significantly smaller by reducing the bias resistance of the TES pixels. We are developing surface micromachining techniques to fabricate TES microcalorimeters on silicon nitride platforms suspended several microns over a silicon substrate [11]. In the future, it may be possible to integrate the in-focal-plane MUX pixels underneath the silicon nitride platforms in surface micromachined arrays, eliminating the need for superconducting bump bonds.

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References

[1] J.A. Chervenak, K.D. Irwin, E.N. Grossman, J.M. Martinis, C.D. Reintsema, M.E. Huber, Appl. Phys. Letters 74 (1999) 4043.

[2] P. J. Yoon, J. Clarke, J.M. Gildemeister, A.T. Lee, M.J. Myers, P.L. Richards, J.T. Skidmore, Appl. Phys. Letters 78 (2001) 371.

[3] D.J. Benford. et al., Proceedings of the 9th International Workshop on Low Temperature Detectors (AIP, 2001), Madison, WI, July 2001, (605) 589.

[4] M. F. Cunningham, J. N. Ullom, T. Miyazaki, S. E. Labov, John Clarke, T. M. Lanting, Adrian T. Lee, P. L. Richards, Jongsoo Yoon, H. Spieler, Appl. Phys. Lett. 81 (2002) 159.

[5] W.S. Holland et al., MNRAS 303 (1999) 659.

[6] W.D. Duncan et al., Proceedings of the 9th International Workshop on Low Temperature Detectors (AIP, 2001), Madison, WI, July 2001, (605) 577.

[7] W. Doriese et al., these proceedings.

[8] C.D. Reintsema, J. Beyer, S.W. Nam, S. Deiker, G.C. Hilton, K.D. Irwin, J.M. Martinis, J. Ullom, L.R. Vale, M. MacIntosh, Review of Scientific Instruments, in press.

[9] G.C. Hilton, K.D. Irwin, J.M. Martinis, D.A. Wollman, U.S. Patent US6239431, filed Nov. 24, 1998.

[10] J.N. Ullom et al., these proceedings.

[11] G.C. Hilton, J.A. Beall, S. Deiker, J. Beyer, L.R. Vale, C.D. Reintsema, J.N. Ullom, and K.D. Irwin, IEEE Trans. Appl. Supercond., in press.